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Observation of nuclear dechanneling for high-energy protons in crystals

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A B S T R A C T

Channeling in a short bent silicon crystal was investigated at the CERN SPS using 400-GeV/c protons with an angular spread much narrower than the critical channeling angle. Particle dechanneling due to multiple scattering on the atomic nuclei of the crystal was observed and its dechanneling length was measured to be about 1.5 mm. For a crystal with length comparable to such dechanneling length, an efficiency of 83.4% was recorded, which is close to the maximum value expected for a parallel beam and exceeds the previously known limitation of deflection efficiency for long crystals.

High-energy charged particles entering the crystal with angles relative to the crystal planes smaller than the critical channeling angle $\theta_c = (2U_0/pv)^{1/2}$, where p, v are the particle momentum and velocity and U_0 the well depth of the crystal potential averaged along the planes, can be captured into the channeling regime [1]. Channeled particles move through a crystal oscillating between two neighboring planes. The averaged planar potential gives an approximate description of channeling, in which the transverse energy of particles is the motion integral. Collisions with atomic electrons and nuclei of the crystal change the transverse energies of particles and as a result they leave the channels (dechanneling).

The average square of the angle of particle multiple scattering on the crystal electrons (MSE) and nuclei (MSN) is proportional to their local density [1,2]. The atomic nuclei density is quickly

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reduced with the distance x from the planes according to a Gaussian distribution $P_n(x) \sim \exp(-x^2/u_\perp^2)$, where $u_\perp = \sqrt{2}u_1$ and u_1 is the amplitude of the thermal vibrations of the crystal atoms. The amplitude u_1 determines the "nuclear corridor" width where particles undergo a strong MSN. It is much smaller than the channel width d_p for the main crystal planes. For instance, for the (110) silicon channels at the room temperature one has $6u_1/d_p = 0.23$. In the central areas of the planar channels particles undergo only scattering on the crystal electrons. The average square of the MSE angle is considerably smaller than for MSN. The critical approach distance to the crystal planes $r_c(u_1)$ is used to determine the boundary of the area of the stable channeling states with the particle oscillation amplitudes $\bar{x}_m \leqslant \bar{x}_{mc} = d_p/2 - r_c$ (the coordinate $\bar{x}$ is measured from the channel center $\bar{x} = x - d_p/2$). Particles leave the stable channeling states through multiple scattering on the crystal electrons. The process has the exponential character, $N_{ch}(z) \sim \exp(-z/L_e)$, where L_e is the "electronic" dechanneling length due to MSE.

Particles with the large oscillation amplitudes $\bar{x}_m > \bar{x}_{mc}$ quickly leave the bound states through a strong MSN near the channel walls. This process can be also characterized by "nuclear dechanneling length" $L_n \ll L_e$ [3]. So, the dechanneling process has two stages. In the first stage particles leave the stable states due to MSE and then they leave the unstable bound states with $\bar{x}_m > \bar{x}_{mc}$ mainly due to MSN, therefore the total dechanneling length $L_d = L_e + L_n$. In all previous measurements with high-energy charged particles [4–9] the crystals with length $L \gg L_n$ were used. The measured value L_d, which characterizes the channeled fraction reduce with the beam penetration depth into the crystal, gives the electronic dechanneling length because $L_d = L_e + L_n \approx Le$. For 400-GeV/$c$ protons in straight (110) silicon crystal L_e should be about 20 cm according to the extrapolation of the available data [7].

Bent crystals can deflect high-energy charged particles being in channeling states [10]. The crystal bend gives the angular unfolding of the dechanneling process because particles dechanneled at the crystal depth l are deflected by the angle $\theta = l/R$, where R is the crystal bend radius. This was used to measure the electronic dechanneling length in [5,8]. The experimental data [8] have shown that a good approximation for the critical approach distance is $r_c = 2.5u_1$. The crystal bend reduces the dechanneling length of particles mainly due to the decrease of the potential well depth,

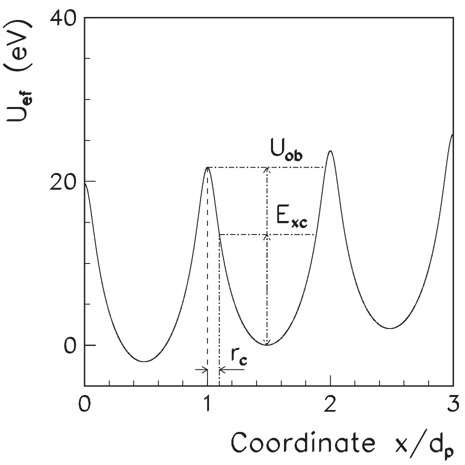


Fig. 1. The effective potentials for the (110) planes of a silicon crystal bent with the radius $R = 38$ m. The coordinate x is measured in the direction opposite to the radial one, $d_p = 1.92$ Å is the channel width. $U_{ob} = 21.7$ eV is the depth of the planar potential well, $r_c = 2.5u_1 = 0.1875$ Å is the critical approach distance. $E_{xc} = U_{ef}(r_c) = 13.52$ eV is the critical transverse energy for stable channeling states.

$L_d(R) \approx L_d(\infty)(1 - R_c/R)^2$, but when $R \gg R_c$, where R_c is the critical bend radius [10], the dechanneling length is about the same as in the straight crystal.

In the present work, a short bent crystal of a length close to L_n was used to study the deflection of 400 GeV/c protons. The fast dechanneling stage due to MSN was detected and a record value of the deflection efficiency P_d was measured, which surpasses the known limitation for long crystals (see Eq. (4) below).

The effective planar potential U_{ef} (see Fig. 1), which governs the transverse particle motion, has a full depth of $U_{ob}(R)$ that depends on the crystal radius of curvature R. Particles with an initial transverse energy E_{xo} not exceeding $U_{ob}(R)$ are captured into the bound states with the planar channels. In the first approximation, the deflection efficiency value P_d of particles by a bent crystal is the product of the capture efficiency P_c into the bound states and the probability $P_{ch} = \exp(-L/L_{e,n})$ to keep particles in the states during the whole crystal length

$$P_d(R) \approx \int_0^{U_{xc}(R)} f(E_{xo})\,dE_{xo} \cdot \exp\bigl(-L/L_e(R)\bigr) + \int_{E_{xc}(R)}^{U_{ob}(R)} f(E_{xo})\,dE_{xo} \cdot \exp\bigl(-L/L_n(R)\bigr), \tag{1}$$

where $f(E_{xo})$ is the distribution of the initial transverse energy of particles at the crystal entrance, $E_{xc}(R) = U_{ef}(r_c, R)$ is the critical transverse energy for the stable channeling states. In long crystals, with length $L \gg L_n$, only particles captured into the stable channeling states with the initial transverse energies $E_{xo} < E_{xc}$ can be deflected. Probability to be in the stable channeling states is limited by dechanneling of particles due to MSE. Therefore, a good approximation for the deflection efficiency in this case is given by the first term of (1)

$$P_d(R) \approx P_c(E_{xo} < E_{xc}) \cdot P_{ch}(L_e) = \int_0^{E_{xc}(R)} f(E_{xo})\,dE_{xo} \cdot \exp(-L/L_e). \tag{2}$$

This also implies that the deflection efficiency is smaller than the capture efficiency of particles into the stable channeling states

$$P_d < P_c(E_{xo} < E_{xc}). \tag{3}$$

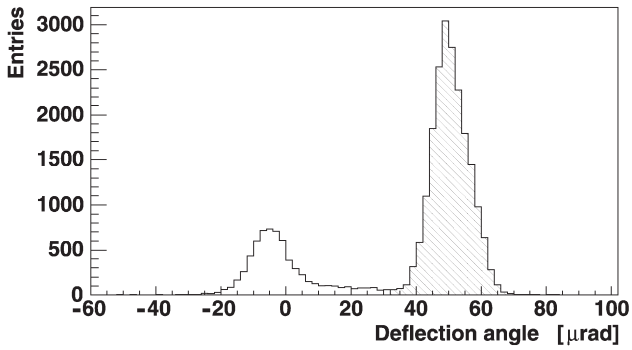
The value of P_c is maximal for a parallel beam aligned with the crystal planes. Its upper limit is realized in a straight crystal and, in the case of (110) silicon channels, is

$$P_c = 1 - 2r_c/d_p = 0.805. \tag{4}$$

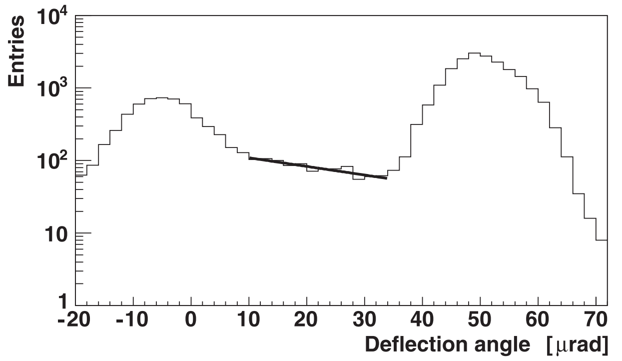
The maximum value of P_d measured in long silicon crystals is about 50%, as reported in [6]. The data were collected using a silicon crystal 50 mm long, (111) oriented, with a bend angle of 1.4 mrad, interacting with an incoming beam of 450-GeV/c protons with a narrow angular spread (RMS = 3 μrad).

Our experimental setup was the same described in [11]. Four microstrip silicon detectors, two upstream and two downstream of the crystal, were used to detect the particle trajectories with an angular resolution of 3 μrad, which is limited by the multiple scattering of particles in the detectors and the air.

A $70 \times 1.94 \times 0.5$ mm^3 silicon strip crystal with the largest faces parallel to the (110) crystallographic planes was fabricated according to the methodology described in [12,13]. The strip-crystal was bent along its length and placed vertically, so that the induced



(a)



(b)

Fig. 2. The distribution of deflection angles for 400-GeV/c protons in the silicon crystal bent along (110) planes, the crystal length is 1.94 mm. Only particles hitting the crystal with the horizontal and vertical angles $|\theta_{xo}|$, $|\theta_{yo}| < 5$ μrad were selected. (a) The deflected fraction 76.6% is hatched. (b) Logarithmic scale along Y axis. The exponential fit, which gives the nuclear dechanneling length, is shown by the line between the two maxima.

anticlastic bending along the crystal width was used to deflect particles in the horizontal plane (see Fig. 2b in [11]). Note that the first use of strip crystals with anticlastic curvature was reported in [14].

The beam of 400-GeV protons had the RMS values of the horizontal and vertical angular divergence of $\sigma_x = (9.27 \pm 0.06)$ μrad and $\sigma_y = (5.24 \pm 0.03)$ μrad, respectively. A high precision goniometer, with an accuracy of 2 μrad, was used to orient the (110) crystal planes parallel to the beam direction. An angular scan was performed and the optimal orientation was selected, which gives the maximum of the deflected beam fraction. Figs. 2a and b show, in linear and semi-logarithmic scale respectively, the distribution of the particle deflection angles at the optimal crystal orientation for the incident beam fraction with horizontal and vertical angles in the range $|\theta_{xo}|$, $|\theta_{yo}| < 5$ μrad. A Gaussian fit of the right peak provides the mean value $\theta_d = (50.5 \pm 0.1)$ μrad and the RMS deviation $\sigma_d = (5.67 \pm 0.04)$ μrad of the beam fraction deflected by channeling. In the assumption of a uniform bending, the anticlastic bend radius is $R = T/\theta_d = 38$ m, where $T = 1.94$ mm is the crystal length along the beam direction. The fraction of particles deflected by angles greater than $\theta_d - 3\sigma_d$ (hatched area in Fig. 2a) determines the deflection efficiency P_d. For the considered case $P_d = (75.2 \pm 0.7_{\text{stat}} \pm 0.5_{\text{syst}})$%.

The peak on the left side in Figs. 2a and b is due to particles, which were not captured into the channeling states at the crystal entrance. They were deflected in the opposite direction due to volume reflection [3]. Particles with deflection angles between the two maxima in Figs. 2a and b are the dechanneled ones, which were lost due to the MSN. Using the relation $l = R\theta$ between the deflection angle θ and crystal length l traversed by a particle before the dechanneling event, the exponential fit of the area of dechanneling (see the line in Fig. 2b) gives the value of the nuclear dechanneling length $L_n = (1.53 \pm 0.35_{\text{stat}} \pm 0.20_{\text{syst}})$ mm. The simulation results based on the model described in [15], in which the average square of multiple scattering angle on the crystal nuclei is proportional to the density of nuclei [2] $\bar{\theta}_n^2 \sim P_n(x)$, gives a close value $L_n = 1.5$ mm.

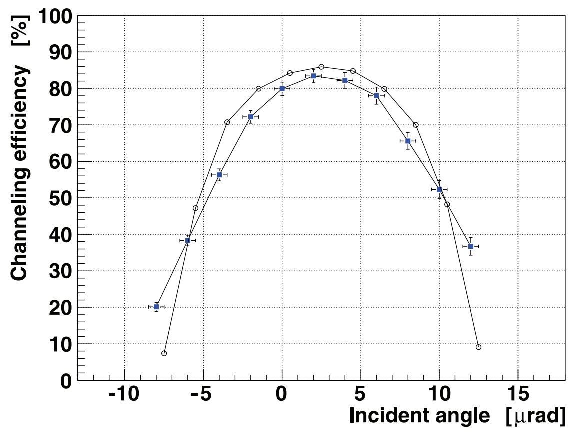


Fig. 3. (Color online.) The deflection efficiency for a narrow beam fraction, which is inside an angular window of 2 μrad width, as a function of the window center position. The maximum value of the efficiency is $(83.4 \pm 1.6_{\text{stat}} \pm 0.9_{\text{syst}})$%. Circles indicate the simulation results.

The deflection efficiency as a function of the incident angle of particles was studied by selecting different angular fractions of the incident beam. The fractions of particles with horizontal incident directions inside contiguous angular windows each of 2 μrad width were selected. Fig. 3 shows the measured deflection efficiency values (blue squares interconnected by segments) for each beam fraction as a function of the window center position. The maximum value of the deflection efficiency corresponding to the optimal choice of the incoming particle directions is $P_d = (83.4 \pm 1.6_{\text{stat}} \pm 0.9_{\text{syst}})$%. Such a value is much larger than the upper limit value for long crystals (4). The simulation results are shown in Fig. 3 as circles interconnected by segments. The agreement of simulation and experimental results is rather good in a wide range of incident angles, around the incoming beam axis. The selected angular window width of 2 μrad is much smaller than the critical channeling angle, whose value is $\theta_{cb} = 10.4$ μrad. For this reason, the observed deflection efficiency is close to its maximum value for a parallel beam.

The measurements have been also performed with a quasimosaic silicon crystal [16] 0.84 mm long, bent along (111) planes with the radius $R = 11.2$ m, resulting in a deflection efficiency of 72%. This is a high value, considering that the stronger bend caused the decrease of the channel potential depth with respect to the above-mentioned case of the short strip crystal.

Short bent crystals producing small deflection angles, as the crystals used in our experiment, are expected to be fully adequate for beam halo collimation [17]. The crystal deflector as a primary collimator instead of a solid target directs the collider beam halo particles deeply onto the absorber. This should significantly improve the collimation efficiency. The key factor for this purpose is the value of possible deflection efficiency for the beam halo particles, which cross the crystal with a small angular spread.

Our experimental results show that the deflection efficiency limit of higher than 80% for a nearly parallel beam predicted by theory in a single passage through a short crystal is really achievable. A fast stage of particle dechanneling due to multiple scattering on the atomic nuclei has been observed. The measured value of nuclear dechanneling length allows estimating the deflection efficiency for all possible applications of short crystal deflectors.

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